CONTRIBUTION TO THE EXTRAGALACTIC X-RAY BACKGROUND FROM CLUSTERS OF GALAXIES

by

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ABSTRACT

We have computed the contribution to the extragalactic background from clusters of galaxies in the 2-6 keV band. We considered two different cluster luminosity functions and two different models for cluster evolution; we assumed a cluster x-ray luminosity-temperature relationships of the type $L \alpha T^{\alpha+1/2}$. We carried out calculations for four different model universes. We find that the overall contribution of clusters to the background is approximately 10% of the total observed x-ray extragalactic background, and that a broad iron line feature of equivalent width of approximately 150 eV is superimposed on the observed background. This result is quite insensitive to the different set of assumptions made in our calculation.

I. INTRODUCTION

The observation of a diffuse x-ray background extending over a broad range of wavelengths has led to several attempts to set limits on the luminosity and density of unresolved point sources which might explain all or part of the background (Silk, 1973, Schwartz and Gursky, 1974). The discovery of extended sources of x-ray emission associated with clusters of galaxies (Byrum et al., 1966, Culhane, 1977, Bachall, 1977) led several investigators (Silk, 1973, Schwartz and Gursky, 1974) to suggest that the diffuse hard x-ray background ($E > 2$ keV), which is known to be of extra galactic origin, might be explained in large part by these sources. More refined observations of the background (Gursky and Schwartz, 1977) and improved estimates of the luminosity function of clusters (Schwartz, 1978, McHardy, 1978) suggest that clusters can account for only 10% of the x-ray background in the energy range 2-10 keV (Gursky and Schwartz, 1977) and have a softer spectrum than the background at higher energies. Recent HEAO-B results suggest that active galaxies and quasars may account for a significant fraction of the remainder of the background (Jones et al., 1979), although a significant contribution to the background due to diffuse material between clusters is not yet excluded.

Cluster sources do, however, contain a prominent spectral feature at 6.7 keV which may allow a more precise determination of their contribution to the background, and provide a test for models of the distribution of clusters in space and evolution of the hot gas in the cluster which is responsible for the x-ray emission. This spectral feature, unresolved

in present data, is due to the superposition of several line multiplets resulting from transitions in the hydrogen and helium-like ions of iron in the dilute intracluster gas bound in clusters (see, for example, Bachall and Sarazin, 1977, 1978). Spectral features attributed to iron have been found in all of the cluster sources so far observed with sufficient sensitivity and resolution, with equivalent widths between 300 and 1000 eV. More than 50 discrete x-ray sources associated with clusters have now been identified, with 3C 343.1 at $z = 0.75$ being the most distant. These observational data have been used to construct preliminary luminosity functions, and thermal models of the cluster sources. Using these results, we have calculated the contributions of distant cluster sources to a predicted spectral feature near 7 keV in the diffuse x-ray background for an isothermal cluster model and for two different assumptions regarding the evolution of the intracluster gas. Comparison of these results with observations of the spectra of the background may allow constraints to be placed on the distribution of clusters or the evolution of the thermal structure of the intracluster gas.

II. FORMULATION OF THE PROBLEM

Approach

We assume that at each epoch a single luminosity function for all clusters $\frac{d^2N}{dzdL}(L,z)$ may be defined, and that the spectra of each cluster, $F[L,z,\nu(1+z)]$ (ergs/sec-keV) depends only on luminosity L and redshift z (or epoch). This assumption implies that there exists a relation $L = L(T,z)$ at each epoch between cluster thermal bremsstrahlung temperature (T) (or between a single thermal parameter in the case of non-isothermal models) and cluster luminosity (L).

It is possible to determine the luminosity function for the present epoch, $\frac{d^2N}{dzdL}(L,z)\big|_{z=0}$ directly from observational data for the brightest clusters ($L \geq 10^{44}$), which make the major contribution to the integrated cluster luminosity. For clusters of lower luminosity, there is more uncertainty in the shape of the luminosity function.

We do not believe that the assumption that a single relation exists between luminosity and temperature for all epochs is unduly restrictive, since the final integrated background luminosity is not strongly dependent on the form of this relationship.

There is little observational data available to select from among the various evolutionary models which have been proposed. We have carried out computations for two different evolutionary scenarios, which we believe are representative of the proposed evolutionary models.

The integrated background luminosity $f(\nu)$ due to a distribution of clusters with luminosity $F[L,z,\nu(1+z)]$ at redshift z can be expressed (Petrosian et al., 1969)

$$f(\nu)d = \int_{L_{min}}^{L_{max}} dL \int_{z_{min(L)}}^{z_{max}} dz \quad \frac{F[L,z,\nu(1+z)]d\nu}{4\pi D^2(1+z)} \frac{d^2N}{dzdL} (L,z)$$

where D is the luminosity distance (which depends on the geometry of the universe model assumed).

We carried out calculations for 4 different model universes:

- steady state model
- Friedman-Lemaitre models, with $\Lambda = 0$

$k = +1,\ q_o = 1$

$k = 0,\ q_o = 1/2$

$k = -1,\ q_o = 1/4$

Our final results are not strongly affected by the choice of model universes (our results differ by only a few percent for the various models), hence we will present here results only for the Friedman-Lemaitre model with $k = 0,\ q_o = 1/2$.

The integration limit of the integral over the luminosity function, L_{min}, is selected to exclude those clusters which are resolvable in the observational data with which the calculation is to be compared. We have carried out the calculation for two minimum detectable cluster flux levels, ℓ, 2.5 Uhuru counts (the minimum detectable level for Uhuru) and 0.5 Uhuru counts (the minimum detectable cluster flux level for the HEAO A-1 experiment). Note that the lower limit of the integral over z thus becomes a function of L. The level of 0.5 Uhuru counts corresponds to a minimum detectable luminosity of approximately 3.7×10^{44} ergs/sec at $z = 0.1$ in the 2-6 keV band (this is somewhat dependent on the assumed relationship between luminosity and temperature).

III. SELECTION OF THE RELEVANT PARAMETERS

A. The Cluster Luminosity Function

Schwartz (1978a) and McHardy (1978) have derived cluster luminosity functions from observational data. The original functions derived by Schwartz is shown in figure 1 and takes the form

$$\psi_1(L) = 7.9 \times 10^{-7} L_{44}^{-2.45} / \text{Mpc}^3 (10^{44} \text{ergs/s})$$

for $L_{44} > 1$, where L_{44} is the cluster luminosity in the 2-6 keV band in units of 10^{44} ergs/sec. At lower luminosities the original work of Schwartz supports the lower curve [$\psi_1(L)$] which has the form

$$\psi_1(L) = 4.5 \times 10^{-7} \exp(-L_{44}/2) / \text{Mpc}^3 (10^{44} \text{ergs/s}) \text{ for } L_{44} < 1$$

The dotted curve shows the extrapolated luminosity function which is obtained if all Abell clusters were assumed to be x-ray sources. More recent data analyzed by McHardy (1978) and Schwartz (1978b) supports the luminosity function $\psi_2(L)$ (figure 1) which is closer to the upper limit established by the dotted curve in figure 1. We have carried out calculations for both ψ_1 and ψ_2. As we show, the two distribution functions give diffuse backgrounds which are not greatly different, since it is the most luminous clusters ($L_{2-6\text{ keV}} > 10^{44}$ ergs) which make the greatest contribution to the background.

B. Cluster Spectra

Sarazin and Bachall (1978) have discussed cluster spectra, based on

isothermal and polytropic hydrostatic models of the thermal structure of clusters. The present data on individual clusters can be fit with either model, with the appropriate choice of parameters. We have chosen to fit the spectra of all clusters with a series of simple isothermal models with varying parameters. The line emission of each intracluster gas is considered to be due to collisional excitation and cascade, and to dielectronic recombination, while the continuum emission is from free-free and recombination radiation (Sarazin and Bachall, 1977). We assumed solar abundances, which is consistent with Perseus, Coma and Virgo clusters analyzed in the light of the model presented (Bachall and Sarazin, 1977). We further assume (following Mushotzky et al., 1978) that the cluster luminosity is related to the temperature by the relation

$$L_{2\text{-}6keV} \propto T^{\alpha+\frac{1}{2}} \quad \text{where } 1.6 \leq \alpha \leq 5.1$$

This assumption is equivalent to the assumption that the emission measure is proportional to T^{α}, since the luminosity of an isothermal bremsstrahlung source is proportional to $T^{\frac{1}{2}}$. For convenience, we have defined 8 cluster luminosity classes with the properties shown in Table 1, and with the luminosity function given by figure 1. We have carried out calculations for 6 values of the parameter α, 1.6, 2.1, 2.6, 3.1, 4.1, and 5.1.

C. Cluster Evolution

Cowie and Perrenod (1978) and Perrenod (1978) have discussed models of cluster evolution. There are not, however, sufficient x-ray data available to constrain the computational models of cluster evolution presented by Perrenod. We have carried out computations for two assumptions regarding cluster evolution:

1. Cluster sources are present with the same density distribution of luminosities and spectra as observed for the present epoch out to a redshift of $z = 3$ (or no evolution).

2. Cluster luminosity evolves according to a model based on the assumption that the intracluster gas is expelled for the cluster member galaxies at a rate which is inversely proportional to the cluster age. Cluster density, and the relationship between luminosity and temperature are assumed to be the same as those derived for the present epoch.

The first assumption is almost certainly incorrect, however, it provides a useful upper limit on the background luminosity due to clusters. We have used the evolutionary model M6 of Perrenod in carrying out the computations based on assumption 2. This model assumes that the conductivity of the intracluster gas is not reduced by magnetic fields, that the material expelled into the intracluster medium has the solar abundance of iron and is at a temperature of 10^8 °K at all times; it predicts that the luminosity of a cluster decreases monotonically with z. Since Perrenod has not carried out computations for a full grid of cluster models, corresponding to the various luminosity classes in our computations, we have assumed that the relationship between luminosity and temperature found for the present epoch ($L \propto T^{\alpha+\frac{1}{2}}$) pertains for earlier epochs as well. The model computations of Perrenod are best fit by $\alpha = 5.1$.

Figure 3 shows how cluster luminosity and temperature evolves according to the model of Perrenod.

IV. RESULTS

In figures 3 and 4 we have plotted the results of our computation for the contribution of clusters to the background for two values of the flux level ℓ above which individual clusters are assumed to be resolvable (2.5 and 0.5 Uhuru counts), for both luminosity functions and for both assumptions with respect to cluster evolution. We have shown only results for three values of α, 1.6, 3.1, and 5.1, in order to avoid overcrowding of the graphs. We have also shown the iron line complex feature superimposed on the observed isotropic background for each set of assumptions. The equivalent width of the iron feature on the background for each set of assumptions considered is tabulated in Table 2. The contribution from clusters of galaxies with the luminosity function ψ_2 is higher than for ψ_1 as expected since we take into account a larger number of clusters with low luminosity. Also the contribution of clusters to a background of flux level below 2.5 Uhuru flux units is higher than for 0.5 Uhuru flux units since in the former case there are less resolved clusters. The contribution of clusters to the background in the case where no evolution is considered is, of course, larger than where evolution is taken into account. Since the evolutionary model considered predicts a small change of luminosity and temperature for $z \leq 0.3$, it does not strongly affect our results. Since the difference between the two results is the order of a few percent, we may conclude that unless there is a strong evolution of the intracluster gas for $z \leq 0.3$ (which would appear to contradict recent Einstein observations, Jones et al. (1979)), we can ignore evolution. In addition we might infer that the contribution of clusters past $z = 3$ is

negligible. In fact, the most striking feature of our results is their insensitivity to the various sets of assumptions made. This insensitivity suggests that:

1. The major contribution to the background comes from clusters of high luminosity ($L > 10^{44}$ ergs/sec) and moderate distance $\sim 0.1 \leq z \leq 0.5$.

2. The predicted contribution is not sensitive to details of the relationship between cluster luminosity and thermal structure.

3. If the predicted line feature is observed, it will provide a test of the cluster luminosity function, but will not significantly constrain models of cluster evolution. This can be seen when considering the line features superimposed on the background. It is impossible to distinguish between the different assumptions made.

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TABLE 1

CHARACTERISTICS OF THE LUMINOSITY CLASSES

Class	Temperature (K)	L_x (α=1.6) 2-6 keV (ergs/sec)	Z_{min} (α=1.6) ℓ<.5 UFU	Density (ψ_1) α=1.6 (#/cm^3)	Density (ψ_2) α=1.6 (#/cm^3)
1	4×10^8	1.1×10^{46}	.36	2.9×10^{-83}	2.9×10^{-83}
2	2×10^8	2.6×10^{45}	.17	2.4×10^{-82}	2.4×10^{-82}
3	1×10^8	6.1×10^{44}	.08	2.0×10^{-81}	2.0×10^{-81}
4	8×10^7	3.8×10^{44}	.05	3.9×10^{-81}	3.9×10^{-81}
5	6×10^7	2.1×10^{44}	.03	9.3×10^{-81}	9.3×10^{-81}
6	4×10^7	8.9×10^{43}	.02	8.7×10^{-81}	1.4×10^{-80}
7	2×10^7	2.1×10^{43}	.01	2.9×10^{-81}	1.8×10^{-80}
8	1×10^7	4.8×10^{42}	.004	7.2×10^{-82}	2.5×10^{-80}

TABLE 2

EQUIVALENT WIDTHS (in eV) OF THE IRON LINE FEATURE AT 7 keV

		ℓ < .5 UFU		ℓ < 2.5 UFU	
	$\psi \diagdown \alpha$	1.6	5.1	1.6	5.1
No	ψ_1	185	129	195	147
Evolution	ψ_2	223	157	217	158
With	ψ_1	165	104	169	114
Evolution	ψ_2	200	114	114	122

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FIGURE CAPTIONS

Figure 1 — The differential luminosity functions ψ, number / Mpc^3 (10^{44} ergs/s), as a function of cluster luminosity in the 2-6 keV band. The plain and dashed lined, ψ_1 and ψ_2 , represent the luminosity function derived by Schwartz and McHardy.

The dotted line gives the limit imposed by the total density of all Abell clusters.

Figure 2 — Evolution of temperature and luminosity derived for the cluster model M6 from Perrenod.

The dashed (plain) curve gives the temperature (luminosity) change with redshift as a function of the temperature (luminosity) at present epoch.

Figures 3 and 4 — The contribution of clusters to the background is shown in the lower group of curves in each figure. The upper curve represents the observed background (Boldt, 1978) with our calculated line feature superimposed.

a. case where the minimum detectable cluster flux level ℓ = 0.5 UFU and the luminosity function is ψ_1

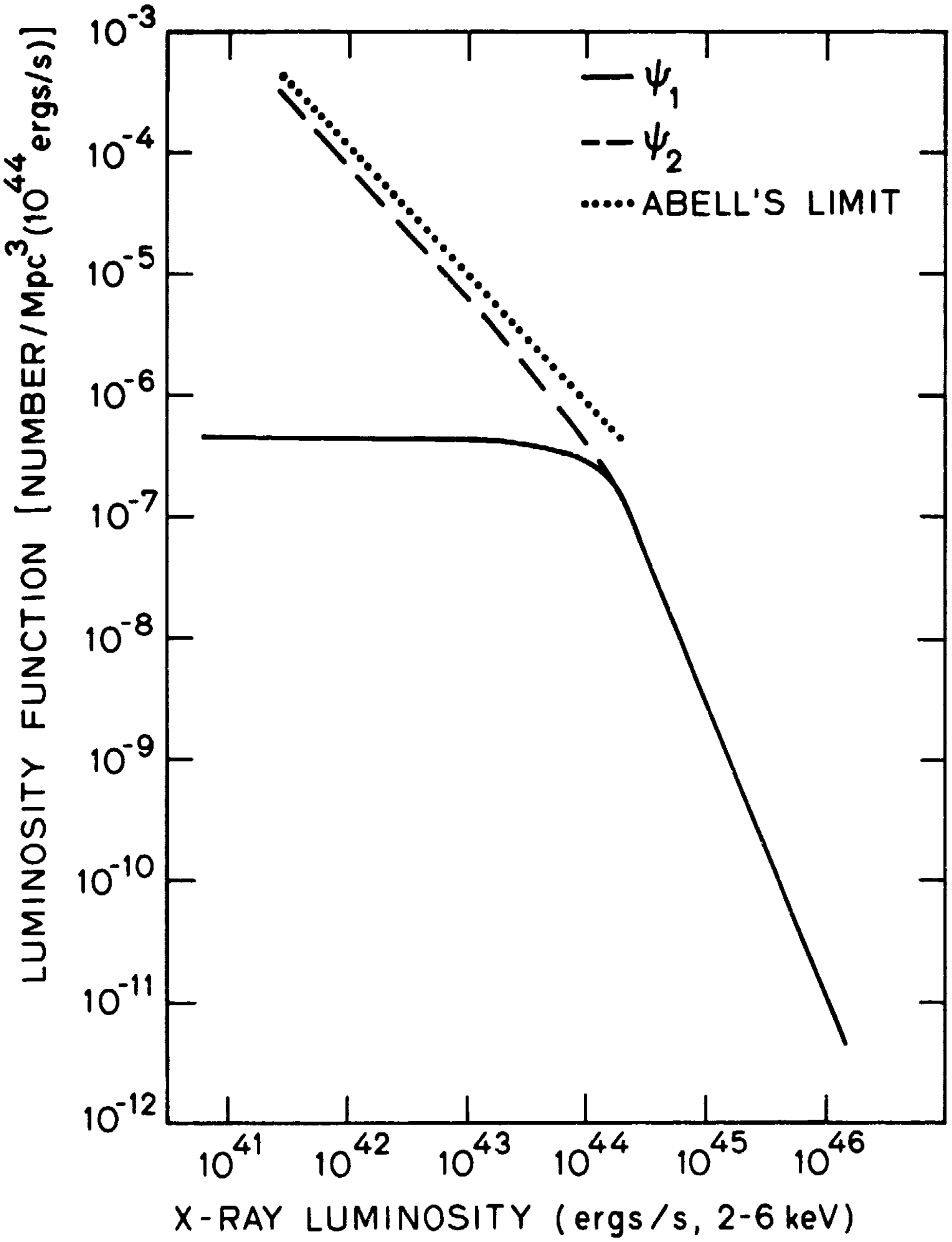
b. ℓ = 0.5 UFU, ψ_2

c. ℓ = 2.5 UFU, ψ_1

d. ℓ = 2.5 UFU, ψ_2

Fig. 3. case where there is no evolution

Fig. 4. case with Perrenod M6 evolution



10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
LUMINOSITY FUNCTION [NUMBER/Mpc^3(10^{44} ergs/s)]
ψ_1
ψ_2
ABELL'S LIMIT
10^{41}
10^{42}
10^{43}
10^{44}
10^{45}
10^{46}
X-RAY LUMINOSITY (ergs/s, 2-6 keV)

FIGURE 1

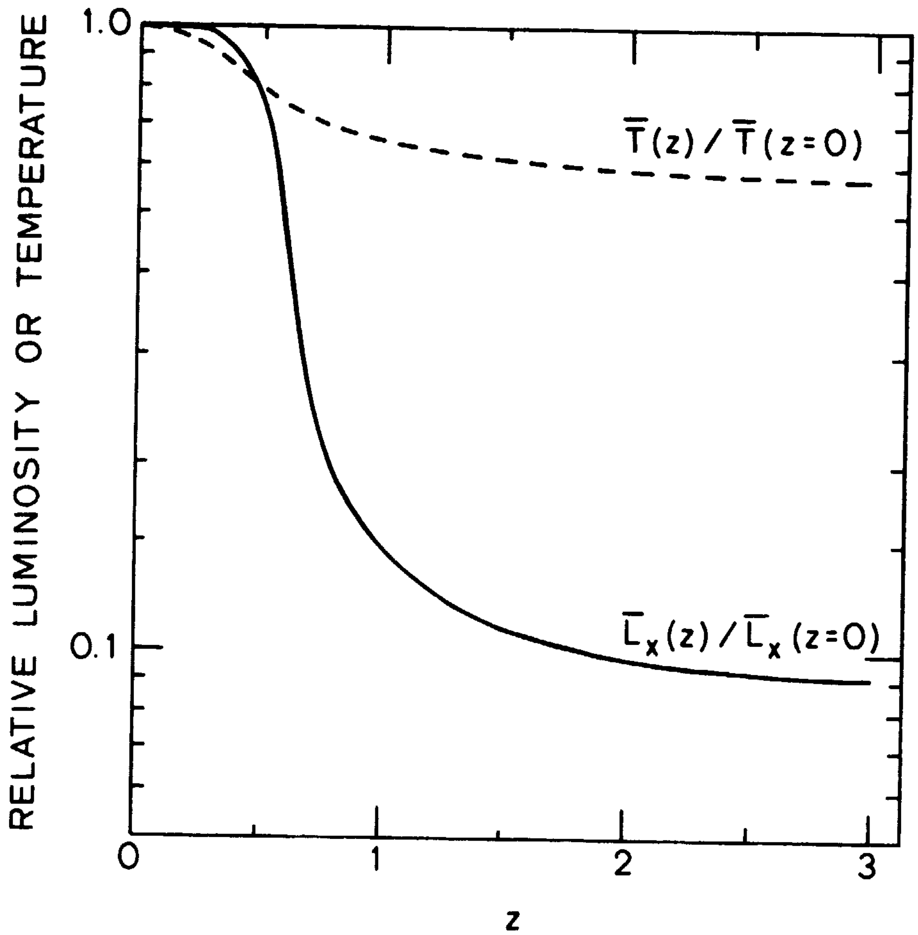

RELATIVE LUMINOSITY OR TEMPERATURE
1.0
0.1
0
1
2
3
z
T̄(z) / T̄(z=0)
L̄x(z) / L̄x(z=0)

FIGURE 2

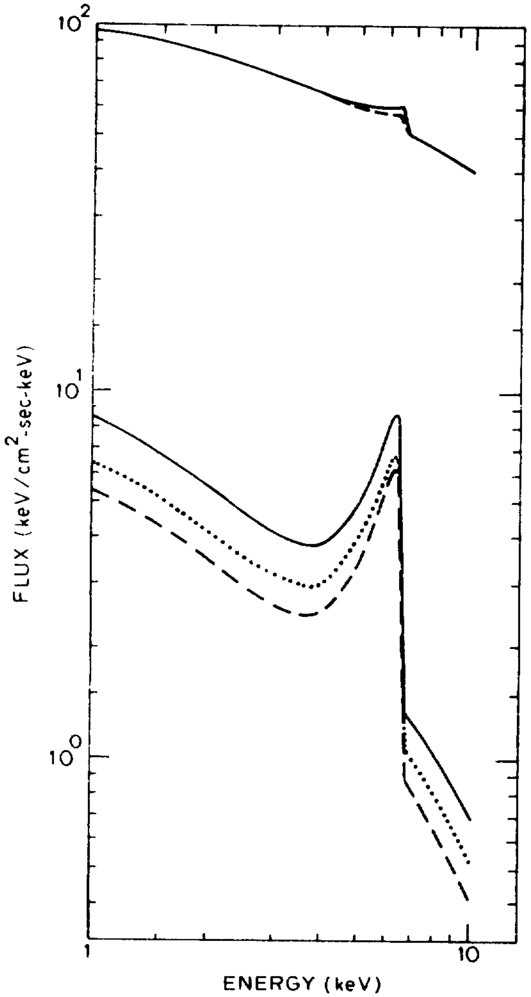


FIGURE 3a

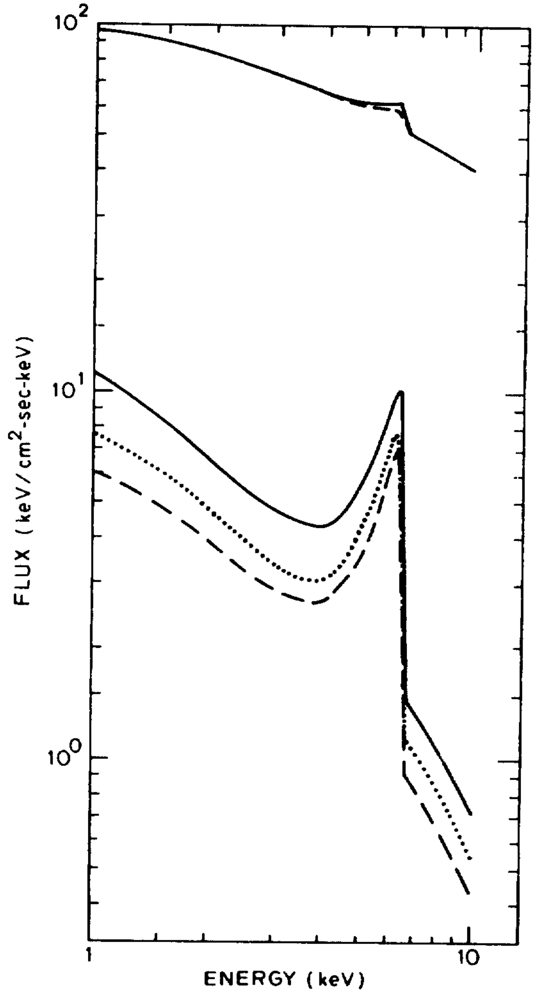


FIGURE 3b

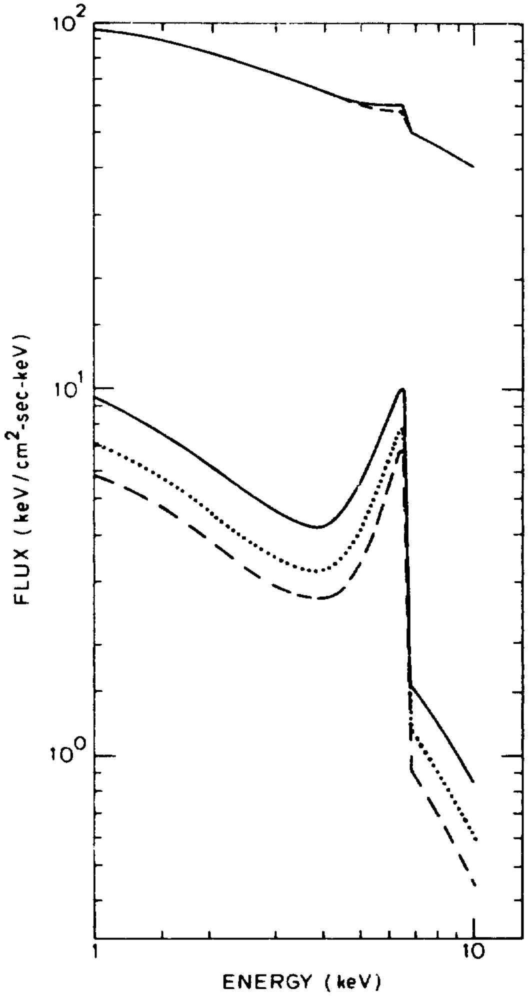


FIGURE 3c

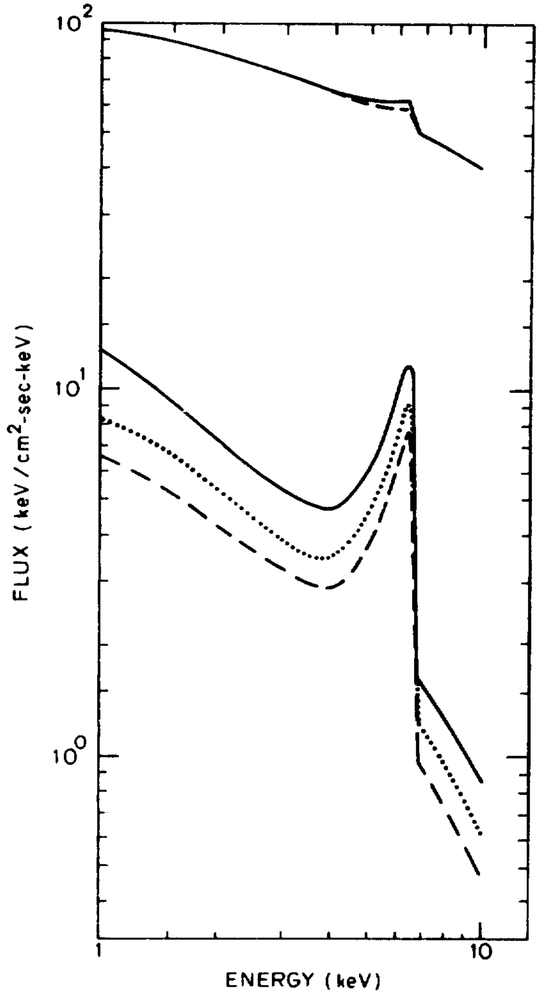


FIGURE 3d

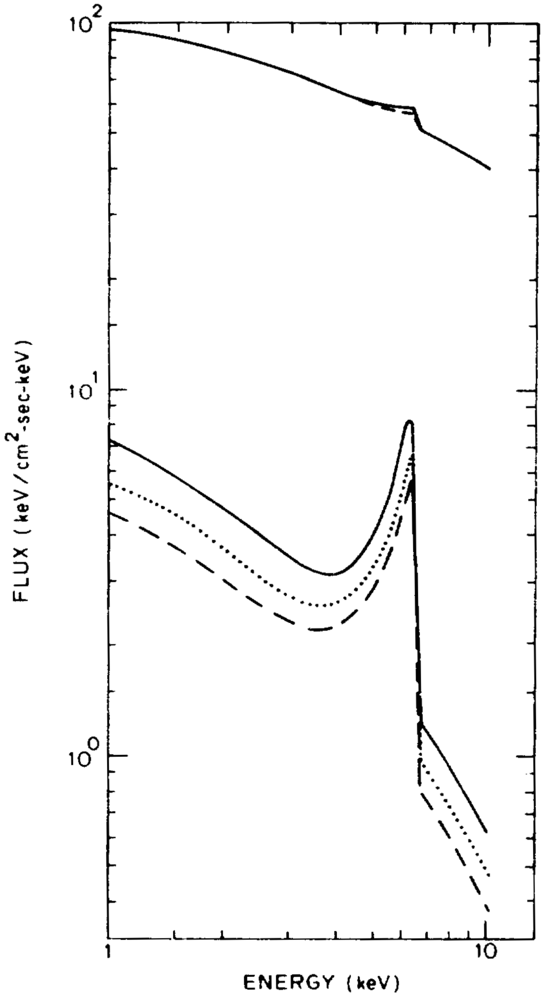


FIGURE 4a

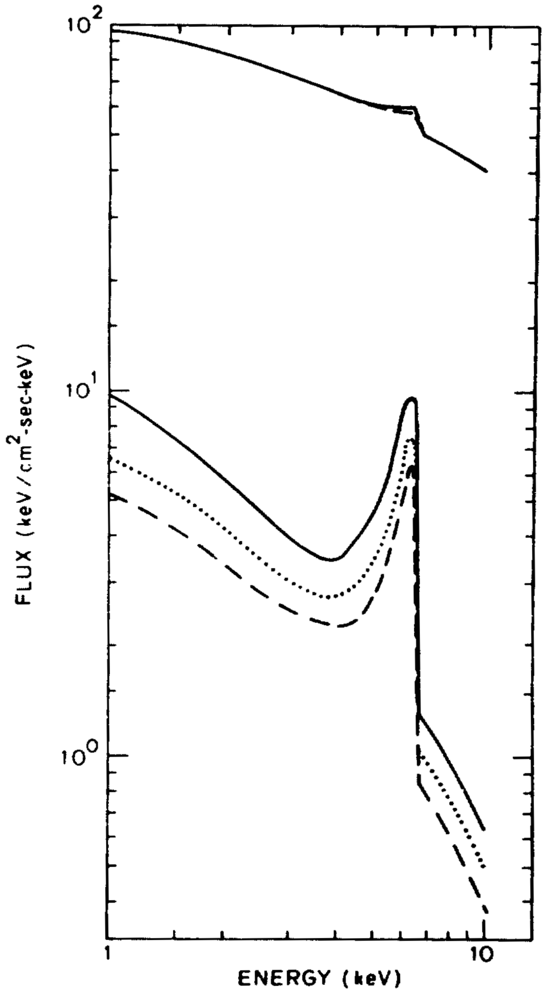


FIGURE 4b

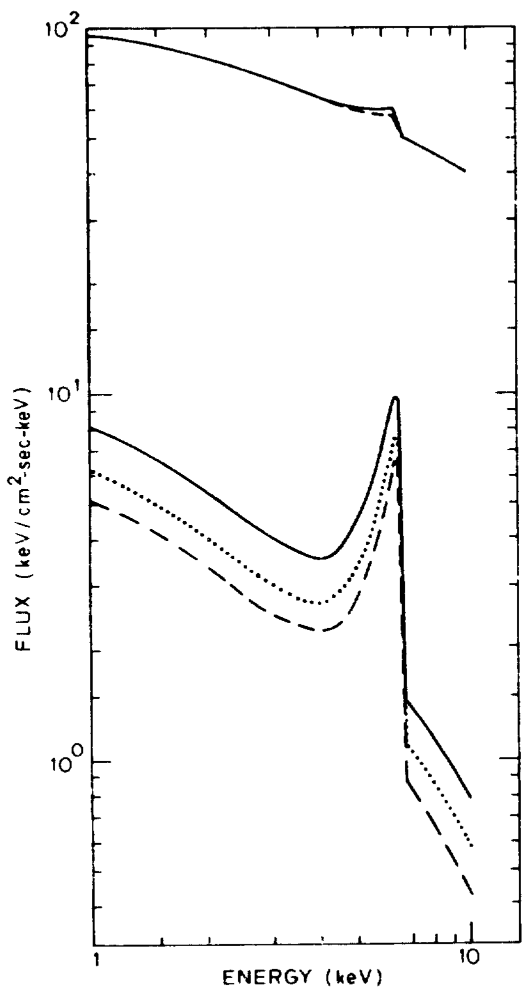


FIGURE 4c

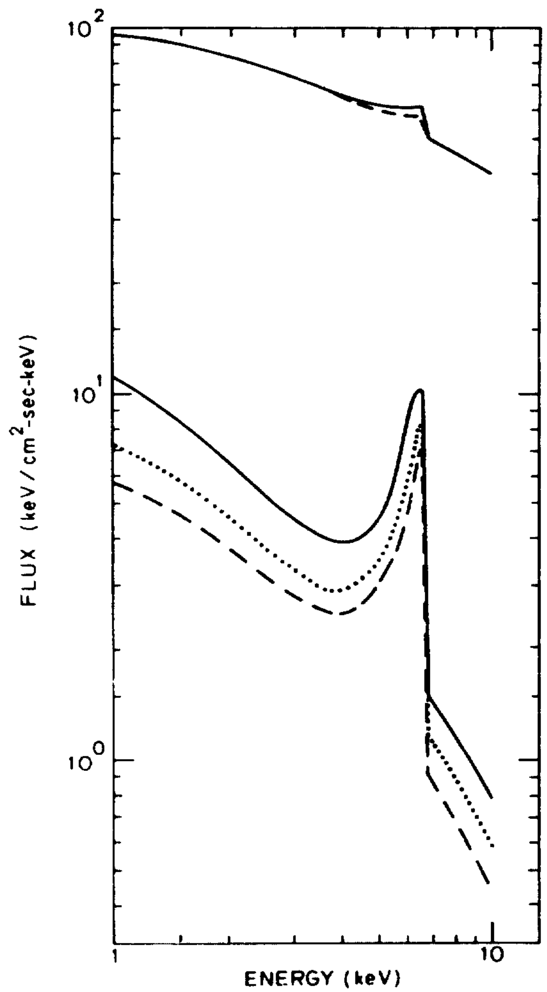


FIGURE 4d